

On the Neural Substrates Leading to the Emergence of Mental Operational Structures

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ABSTRACT

A developmental approach to the study of the emergence of mental operational structures in neural networks is presented. Neural architectures proposed to underlie the six stages of the sensory-motor period are discussed.

1 Introduction

Historically, the study of intelligence has been polarized into explanations based on neurophysiology and those based on logic. The same dichotomy manifests itself in current approaches, the former corresponding to the neural network theory and the latter to the symbolic reasoning schemes used in artificial intelligence (logic, fuzzy logic, etc.). At a first glance these two explanations fail to extend to each other, for logic does not tell us anything about neurophysiology and it seems difficult to explain the rules of logic from the connectivity and firing patterns of neurons. However, logic is housed in neurophysiological substrates and there should be a reconciliation between these two explanations (if we reject dualism). Since logical reasoning emerges as a result of an extensive development and since the early phases of development consist of simpler behaviors, the link between adult intelligence and the underlying neural correlates can be established by relating the early developmental stages to neurophysiological substrates and by studying the adaptive dynamics of the system that leads to the emergence of higher mental operations. The theory of genetic psychology (Piaget, 1967) provides us with a very detailed study of various phases starting from birth to the adulthood. This paper extends various psychological concepts of the theory of genetic psychology to the neurophysiological domain. In particular, it outlines neural networks proposed to give rise to the various stages of the sensory-motor period.

2 A neural theory of development

Our study of development is closely linked to the theory of genetic psychology (Piaget, 1967). Piaget (1963) named the post-natal developmental period where language is absent the *sensory-motor period* and suggested the existence of six consecutive stages that govern its dynamics. These stages start from reflexes and end with mental manipulations of sensory-motor schemes to invent new intelligent structures. Mental internalization of early sensory-motor schemes lead to the capability of applying them to formal reasoning in the adult life.

2.1 The six stages of the sensory-motor level according to the theory of genetic psychology

The first stage of the sensory-motor period consists of simple reflexive sensory-motor behavior. In the second stage, the repetitive use of these reflexes, called “primary circular reactions”, leads to the formation of habits. The primary circular reactions refine genetically encoded reflexes and enable the emergence of multi-modal coordination. At the third stage the infant starts to draw a distinction between the “means” and “ends” and uses “secondary circular reactions”. During the fourth stage, existing sensory-motor schemes are coordinated and extended to new situations. In stage 5, new sensory-motor schemes are acquired through physical groping. Finally during the sixth stage, which marks the end of the sensory-motor level, new sensory-motor schemes are acquired by mental groping.

2.2 A model for primary sensory-motor schemes

We first start by describing the seed sensory-motor circuit with nonassociative learning properties (Öğmen 1991, Öğmen & Moussa, in press). The architecture, which is illustrated in Figure 1, has three main parts: the sensory circuit, the sensory-motor gate circuit, and the motor circuit. Since the model was originally formulated explicitly for the prototypical landing behavior of the fly, the sensory and motor parts are specialized for this animal. The sensory part consists of visual signals conveyed by the compound eyes and of tactile pathways. In the fly, signals from the compound eyes are processed by three optic ganglia: lamina, medulla, and lobula complex, denoted by La , Me , Lo respectively in Figure 1. The output of the visual processing stage results from a behavior sensitive pooling of motion detector neuron activities. In the case of landing, stimuli indicating the approach of a landing site, such as expanding patterns, are detected by an appropriate pooling of directionally selective large field motion sensitive neurons and constitute the “agonist” input to the sensory-motor gate circuit. This input is denoted by V_{an} in Figure 1. Stimuli of opposite character (such as contracting stripes) constitute the “antagonist” input denoted by V_{ag} . Agonist and antagonist tactile inputs are added to these visual signals. One such input is marked by I_{ta} in Figure 1. The following stage, which is a gated dipole anatomy (Grossberg, 1972), constitutes the *sensory-motor gate* network because this is the stage where various sensory signals are pooled to determine whether a motor command signal will be issued. The sensory-motor gate network has agonist and antagonist outputs denoted respectively by x_{ag} and x_{an} . These signals project to motor circuits (not shown) to control agonist-antagonist muscle pairs (indicated by Ag and An). This sensory-motor model exhibits nonassociative learning as observed in the landing reaction of the fly as well as in human infants (Lipsitt 1990).

Figure 2 illustrates this architecture augmented with adaptive capabilities. The adaptive version of this sensory-motor model has also three major parts: sensory, sensory-motor gate, and motor. These parts are augmented by inclusion of adaptive mechanisms similar to those proposed in the INFANT (Kuperstein & Rubinstein 1989) and AVITE (Gaudio & Grossberg 1991) models. x_e represents an environmental variable. These environmental variables are converted into neural activities by the sensory loci. The activities of the sensory loci are denoted by x_s . The sensory loci project to the sensory-motor gate networks. The first layer of the sensory motor gate network consists of nodes interconnected by recurrent on-center off-surround connections. Each node corresponds to the agonist-antagonist inputs of a given sensory-motor scheme. The gated dipole of Figure 1 is represented in a condensed way by a single node in this layer. An arbitrary number of sensory-motor schemes, similar to the one shown in Figure 1, exists. The competition between these nodes selects and triggers one of the sensory-motor schemes. The second layer of

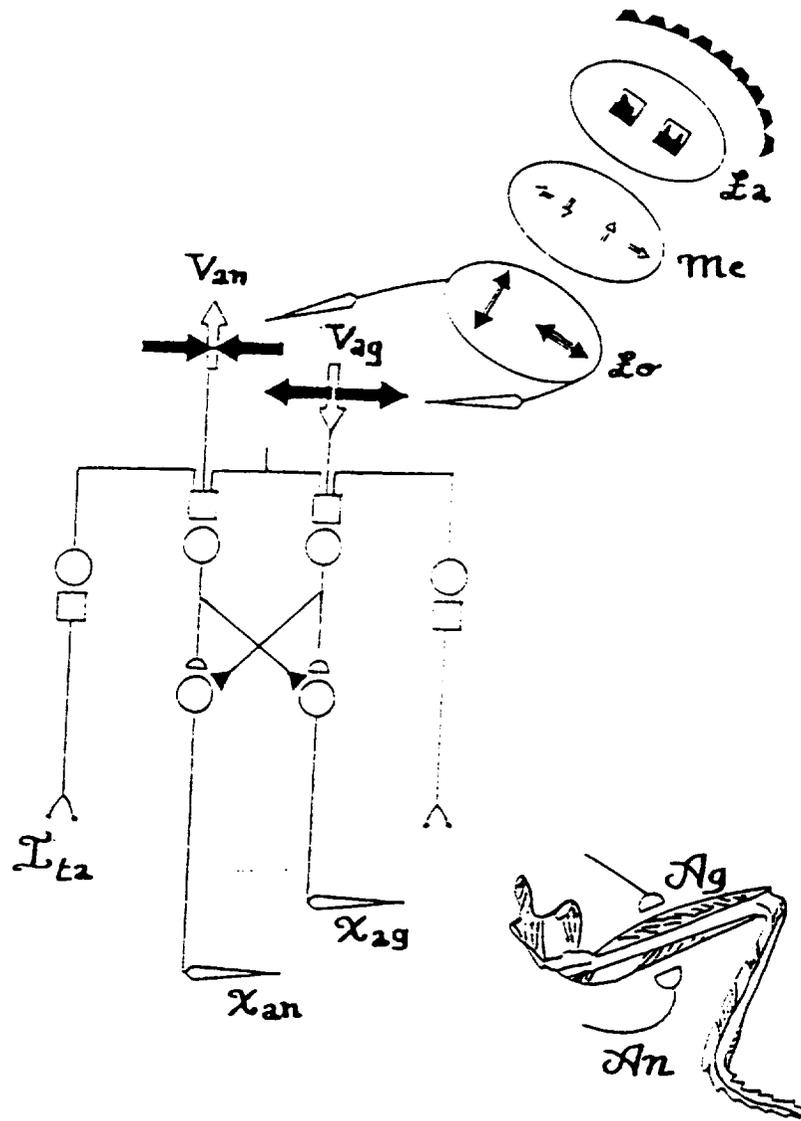


Figure 1: Model for primary sensory-motor schemes (Ögmen & Moussa in press).

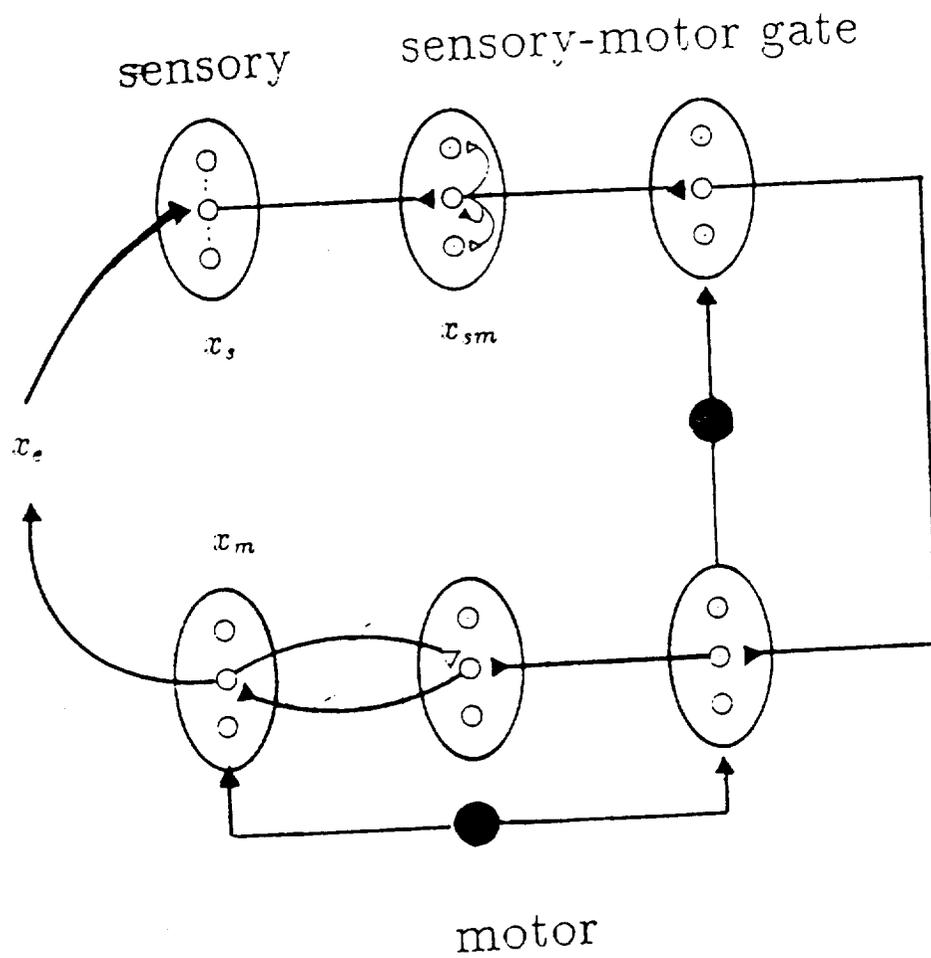


Figure 2: Adaptive version of the sensory-motor model shown in Figure 1.

the sensory-motor gate part is used to convert the representation of the sensory space into the representations of the motor space. The connections converging to this layer are adaptive. The motor part consists of three layers and has AVITE model's anatomy (Gaudio & Grossberg 1991). The output layer produces motor command signals while the input layer receives the desired motor command signals. The layer between these "target" and "present" motor signals computes the error. This organization constitutes a basic feedback control system where the output is driven by an error signal during real-time operation. Moreover, the same "motor error" layer is used to adapt to changes in the plant, making the system an adaptive feedback control system. What is notable in this anatomy is that the same error signals are used both for performance and learning. Another important feature of the AVITE circuit is the "Endogenous Random Generator" (ERG) which generates random postures and enables the spontaneous learning of sensory-motor coordinate transforms. The filled circles depict in a condensed way the function of the ERG. During the active phase of the ERG a random motor signal is dictated to the output of the motor circuit. During the passive phase of the ERG, activity of the motor layer is transferred to the first layer of the motor circuit which is transferred to the buffer layer of the sensory-motor gate network. The arrow from the bottom filled circle to the motor output layer depicts the generation of random motor signals. The pathway from the motor signal level to the motor target level depicts the transfer of activity between these layers during the learning phase. A similar transfer occurs between the motor target layer and the sensory-motor gate buffer layer. Note that, in addition to internal feedback, the sensory-motor circuit constitutes a closed loop through the environmental variable denoted by x_e . The interaction between the environmental variables and neural variables is essential and constitutes an overall organization by the relationship of *assimilation* that unites them (Piaget, 1963).

The circuit described above constitutes the proposed basic neural correlate for the reflexive behavior of Stage 1. The adaptive nature of the circuit requires the use of these reflexes for consolidation and fine tuning. The repetitive use of reflexes leads to the second stage, the stage of habits. Figure 3 shows how the beginnings of "cortexification" occurs at this stage. In Figure 3, the architecture of Figure 2 is depicted in a simplified form as a closed loop of environmental, sensory, sensory-motor gate, and motor variables denoted by x_e , x_s , and x_m respectively. To this basic loop, additional circuits, proposed to be of cortical origin, are added. These cortical networks receive sensorial inputs and have a feedback structure. They are proposed to be adaptive resonance theory (ART) architectures (Carpenter & Grossberg 1988, Grossberg 1976) and each node represents a layer of ART. At this stage, sensorial stimuli start to be recorded and generalized cortically. The outputs of these ART circuits also make connections with the sensory-motor circuits. The connections from ART circuits to sensory-motor loops are proposed to be Hebbian synapses so that an association between the cortical representation of sensory stimuli and the active sensory-motor circuits occurs through the reinforcement of the synaptic weight between the ART circuits and the sensory-motor gate nodes. A second feature of cortical development at this stage is the beginnings of cortico-cortico associations. This is shown by synaptic connections between various ART circuits. This phase of operation corresponds to Stage 2, in that the sensory-motor schemes are not decomposed and consequently there is no differentiation between the "means" and the "ends". The lack of decomposition comes from the property that one cannot, at this point, access these closed loop circuits from an arbitrary entry point and the only way to activate them is to provide the appropriate environmental signals.

During Stage 3, such a decomposition is introduced by the development of "secondary circular reactions". Once the sensory-motor repertoire becomes sufficiently rich and multi-modal coordination (in particular the coordination between vision and grasping) reaches a satisfactory level,

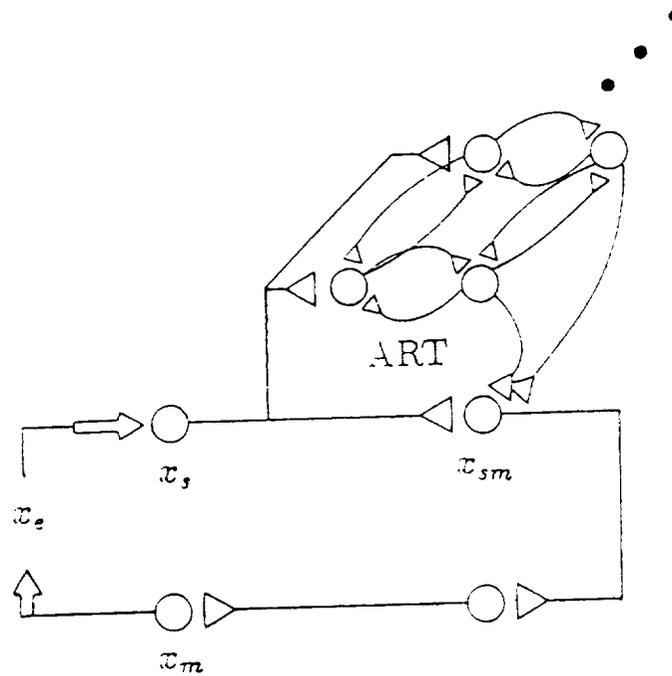


Figure 3: The architecture of Figure 2 is represented in a simplified form as a closed loop of environmental variables x_e , sensory variables x_s , sensory-motor gate variables x_{sm} , and motor variables x_m . To these basic loops additional circuits are added to explain the beginnings of "cortexification".

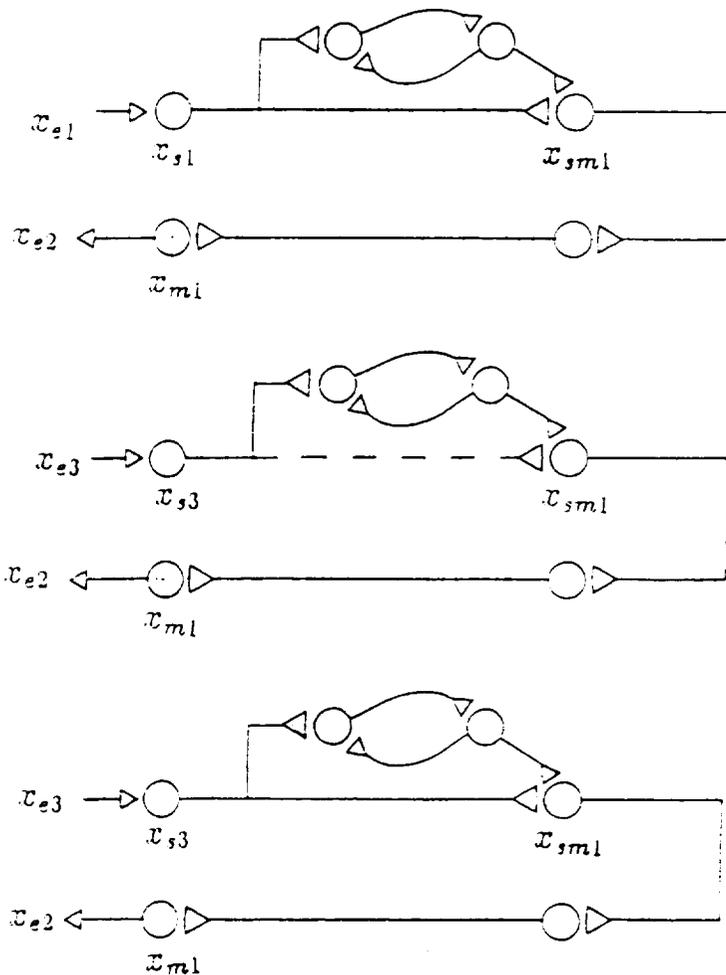


Figure 4: Secondary circular reactions

the infant starts grasping objects placed in her vicinity. Assume that the infant is presented with a toy, grasps the toy, shakes the toy, and that the toy produces a characteristic sound new to the infant. This sound will retrigger the sensory-motor scheme, i.e. will generate a circular reaction. Later, when the infant is presented with a similar toy, she will try the same sensory-motor scheme. Similarly, when the sound of the toy is reproduced by the experimenter, she will look for the toy (Piaget 1963).

Figure 4 illustrates how this occurs in the proposed neural circuits. Initially, a toy is presented (x_{e1}) and it triggers a sensory-motor scheme (grasping and shaking) whose output is a surprising sound (x_{e2}). The sensory-motor scheme is repeated many times until the novelty of stimuli vanishes.¹ During this circular reaction, a connection from the cortical circuits to the sub-cortical circuits is also reinforced. If there are consistent stimuli pairings, association between these stimuli also occurs. In the example of toy shaking, at least an association between the object (x_{e1}) and the sound (x_{e2}) occurs. Later, assume that the infant is presented with a different object x_{e3} and that this object does not trigger directly the grasping scheme (the dotted connection in Figure 4). Now, if this object has an equivalent cortical generalization, it will send a signal to this sensory-

¹In the basic architecture of Figure 2, habituating sensory and sensory-motor gate signals underlie the habituation properties of the circuit.

motor scheme via the cortical connection which was reinforced during the circular reactions. If this signal is strong enough to trigger the sensory-motor scheme without the sensory signal, the infant will shake this new object. If this object also makes a similar sound (x_{e2}), it will re-activate this sensory-motor scheme via a circular reaction. The repetition of the sensory-motor scheme will reinforce the direct sub-cortical connection as shown at the bottom of Figure 4.

While the previous example considered a single sensory-motor scheme for simplicity, in practice a larger number of environmental variables (the first being the object, the last being the sound) are involved.

Note that one can see the important distinction that Piaget drew between his notion of adaptation through an equilibrium between assimilation and accommodation and the associationistic theory of intelligence. While, the behavioral analysis of the network described above may look like an associationistic paradigm, it is important to emphasize that the associations are not passive but involve existing sensory-motor schemes. Initially, x_{e1} and the intermediate environmental variables are assimilated to generate this particular sensory-motor scheme. During this assimilation process, other environmental variables are also registered. This registration is primed by the neural activities occurring in the sensory-motor scheme that is active. The time scales of association (i.e. the inter-stimulus intervals) are not arbitrary but are determined by the temporal characteristics of the active sensory-motor scheme. Later, when x_{e3} is represented to the system, it can activate the same sensory-motor scheme either because it is an equivalent stimulus or because it was associated with x_{e1} during the previous repetitions. Consider the classical example of food bell pairings. The presentation of an object that resembles food will trigger a complex sensory-motor scheme in a dog. The same sensory-motor scheme can also be generated by a different food. Another possibility is that a conditioned stimulus, such as the sound of a bell, is delivered. In a future trial, if this bell is delivered alone it will trigger the sensory-motor scheme. However, following the first phase (salivation) if the appropriate environmental variables cannot be assimilated, the chain of actions will be broken and the global sensory-motor scheme will be aborted (the dogs do not continue to chew etc.). If such a pairing ceases to occur, it will be extinguished. However, assume now that the conditioned stimulus not only generates the initial stages of the sensory-motor scheme but also is accompanied by the appropriate intermediary environmental variables so that a complete assimilation cycle can occur. The successful completion of the assimilation will reinforce the direct path so that this stimulus will be able to generate the whole cycle directly. This change, which consists of an adaptation to the environment, is called *accommodation* (Piaget, 1963).

Once the sensory-motor schemes become accessible via cortical circuits as outlined above, they become decomposed and the essential property of Stage 3 emerges: the distinction between means and ends. A sensory-motor scheme is the means to achieve a goal. The goal corresponds to the final environmental variable or internal variables associated with this external variable. Assume that the infant acquired a sensory-motor scheme consisting of opening a drawer and receiving a new toy. Initially, this sensory-motor scheme can be generated only by the sight of the drawer. Once it becomes decomposed, the infant will look for a drawer with the goal of receiving a new toy.

In stage 4, the decomposed sensory-motor schemes are coordinated into new wholes to achieve new goals. The activation of a new goal can generate multiple or a chain of existing sensory-motor schemes. In the case of multiple activation, the competition at the sensory-motor gate level selects the best alternative. In the case of a chain, the chain gets activated as a whole as long as the appropriate environmental variables can be assimilated. This new grouping becomes reinforced if it leads to the achievement of the goal and can be accessed more readily in the future.

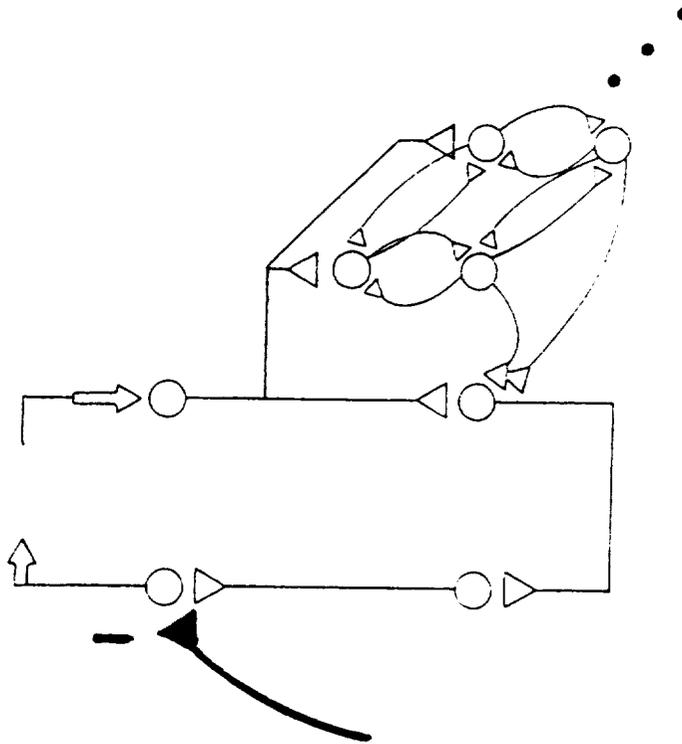


Figure 5: Mental groping: Motor layers are actively inhibited and the infant intentionally activates sensory-motor schemes without motor reactions.

If the existing sensory-motor schemes fail to combine with the environmental variables in order to complete the cycle leading to the achievement of the goal, new means have to be invented. This occurs in Stage 5 by use of physical groping. Assume that the goal activates some existing sensory-motor schemes through the competition at the sensory-motor gate layer. This competition will start with the best possibility and the system will try different schemes. If all fails, the ERG will generate random motor behavior or will bias existing sensory-motor schemes. This constitutes the basis of physical groping. If by chance the resulting behavior reaches the goal, it will be reinforced through circular reactions and will be integrated to the sensory-motor repertoire as a newly discovered means.

The functional operation of Stage 6 is illustrated in Figure 6. At this stage, the motor layers are actively inhibited. This way, the discovery of new means can be disconnected from actual physical action. As a result, the subject can carry out "mental groping" and discover new means without physical contact.

3 Concluding remarks

The early developmental period outlined above indicate that passive perception is inadequate for explaining intelligence and the system should actively explore the environment to generate a rich repertoire of sensory-motor schemes whose abstractions lead to the formal reasoning structures in adult life.

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